

Nickel-catalysed bis-allylation of internal alkynes with triallylindium

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Received (in Cambridge, UK) 10th March 2006, Accepted 20th April 2006

First published as an Advance Article on the web 10th May 2006

DOI: 10.1039/b603663e

The Ni-catalysed reaction of triallylindium with internal alkynes underwent bis-allylation to afford octa-1,4,7-trienes in high yield.

Addition of allylindium reagents (allylindiation) to terminal alkynes provides linear- or branch-type 1,4-dienes depending on the existence or absence of a chelation functionality, in particular a hydroxy group adjacent to the alkyne moiety:¹ propargyl and homopropargylic alcohols undergo allylindiation in an anti-Markovnikov fashion to afford linear-type 1,4-dienes, whereas non-functionalized alkynes give branch-type 1,4-dienes. The allylindiation of inner alkynes, on the other hand, is limited to alkynes bearing a hydroxy group or a trimethylsilyl group and only the benzylindiation of non-functionalized inner alkynes has hitherto been documented.² During our course of study for allylindiation, we found that non-functionalized inner alkynes react with triallylindium in the presence of a nickel catalyst to give octa-1,4,7-trienes selectively in high yields.

Triallylindium, prepared from allylmagnesium bromide and indium trichloride in THF, was allowed to react with 1-phenylprop-1-yne and the results are summarized in Table 1.³ No product was observed without catalyst and the starting alkyne was recovered completely (entry 1). In the presence of Ni(acac)₂, the bis-allylated product **1a** and the mono-allylated product **2a** were obtained (entry 2). The *cis*-geometry of **1a** was determined by comparison with the ¹H NMR in the literature.⁴ The yield of **1a** was increased by increasing the amount of Ni(acac)₂ (entries 3 and 4). The addition of dienes proved useful for improving the yields (entries 5–7), whereas the presence of PPh₃ severely inhibited the allylation (entry 8). Ni(cod)₂ served as a catalyst for the reaction (entry 9), while Pd(acac)₂ and Pt(acac)₂ did not promote the bis-allylation.

The bis-allylations with other alkynes were conducted under the best conditions observed in Table 1. Oct-2-yne gave the corresponding bis-allylated product **1b** quantitatively (Table 2, entry 1). Diphenyl acetylene also underwent the bis-allylation to afford the octa-1,4,7-triene **1c** in modest yield together with the mono-allylated product **2c** (entry 2).

Next, we turned our attention to comparing a variety of allylating agents for the bis-allylation (Table 3). Allylindium diiodide gave **1a** in 13% yield together with **2a** in 7% yield (entry 1). Allylindium sesquiodide⁵ afforded similar results (entry 2). As the best results were obtained with triallylindium among allylindium reagents, we focused on other allylic metal reagents bearing no halogen on the metal (entries 3–5). When triallylgallium

Table 1 Reaction of triallylindium with 1-phenylprop-1-yne

Entry	Catalyst (mol%)	Yield (%) ^a		
		1a	2a	3a
1	None	0	0	0
2	Ni(acac) ₂ (20)	25	4	0
3	Ni(acac) ₂ (50)	58	7	0
4	Ni(acac) ₂ (100)	72	4	0
5	Ni(acac) ₂ (20) + COD (40)	34	6	0
6	Ni(acac) ₂ (100) + COD (200)	83	0	0
7	Ni(acac) ₂ (100) + hexa-1,5-diene (200)	78	4	0
8	Ni(acac) ₂ (100) + PPh ₃ (100)	1	2	1
9	Ni(cod) ₂ (136)	55	3	0

^a Yields of products were determined by GC.

and diallylzinc were employed, a significant erosion of the yields was observed (entries 3 and 4). Allylstannane gave no product (entry 5). Allylmagnesium bromide, the precursor to triallylindium, afforded **1a** in only 20% yield (entry 6), suggesting that the transmetalation into triallylindium is crucial for the successful bis-allylation.

Ikeda and co-workers have reported that the Ni-catalysed reaction of terminal alkynes with allyl chloride and Me₃Al gave the three-component coupling products.⁶ In order to gain some insights into the reaction mechanism of this bis-allylation, we

Table 2 Reaction of triallylindium with alkynes

Entry	R ¹	R ²	Yield ^a (%)	
1	<i>n</i> -C ₅ H ₁₁	Me	1b : 100	
2	Ph	Ph	1c : 34 (40) ^b	2c : 6

^a Yields of products were determined by GC. ^b Recovery of diphenyl acetylene.

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Table 3 Reaction of various allylic metals with alkynes

Ph—C≡C—Me + $\text{CH}_2=\text{CH}-\text{M}$					
		$\xrightarrow[\text{THF, rfx, 16 h}]{\text{Ni(acac)}_2 \text{ (100 mol \%)}} \mathbf{1a} + \mathbf{2a} + \mathbf{3a}$			
		Yield ^a (%)			
Entry	Allylic metal	1a	2a	3a	Recovery
1	(allyl)InI ₂ ^b	13	7	0	50
2	(allyl) ₃ In ₂ I ₃ ^c	9	11	0	21
3	(allyl) ₃ Ga ^d	18	5	1	9
4	(allyl) ₂ Zn ^d	5	5	2	19
5	(allyl)(<i>n</i> -Bu) ₃ Sn	0	0	0	97
6	(allyl)MgBr	20	2	1	1

^a Yields of products were determined by GC. ^b Prepared from allyl iodide and InI. ^c Prepared from allyl iodide and In. ^d Prepared from allylmagnesium bromide and MCl_n.

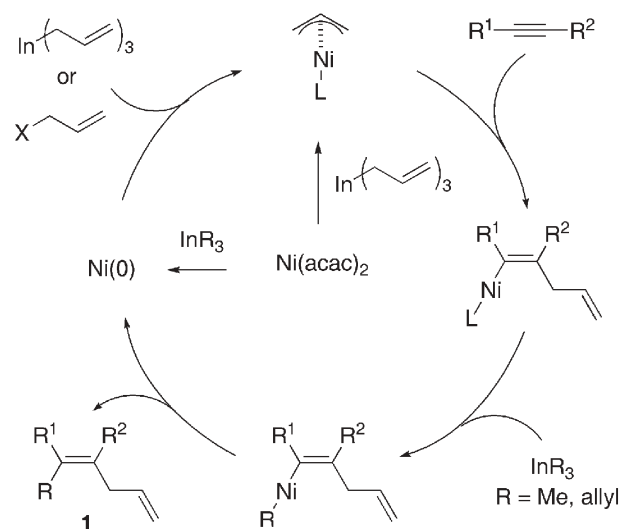
applied Me₃In to the above reaction and found that the results were similar to those observed in the case of Me₃Al (Table 4). The reaction mechanism involving Me₃In is considered to be analogous to that proposed for the reaction of Me₃Al (Scheme 1): Initially a π-allylnickel intermediate is formed from allyl chloride and an active nickel(0) catalyst generated in situ by the reduction of Ni(acac)₂ with Me₃In. The addition of the π-allylnickel(II) to an alkyne gives a vinylic nickel intermediate, which undergoes a cross-coupling reaction with Me₃In affording the products and regenerating the nickel(0) catalyst.

As a logical progression from the above three-component reaction, we initiated an approach to the bis-allylation product by involving triallylindium instead of Me₃In. The reaction of 1-phenylprop-1-yne, triallylindium and allyl chloride was performed in the presence of Ni(acac)₂ (20 mol%) in THF at room temperature. The yield of the bis-allylation product (17%) was, however, less than expected, showing that some side reactions of the π-allylnickel intermediate, such as a cross-coupling with triallylindium, take place prior to the addition to the alkyne.

Table 4 Reaction of trimethylindium and allyl chloride with alkynes^a

R ¹ —C≡C—R ² + Me ₃ In + $\text{CH}_2=\text{CH}-\text{Cl}$					
		$\xrightarrow[\text{THF, rt}]{\text{Ni(acac)}_2 \text{ (5 mol \%)}} \mathbf{2d} + \mathbf{3d}$			
		$\mathbf{2e} + \mathbf{3e}$			
		Yield (%) (2 : 3) ^b			
1	<i>n</i> -C ₆ H ₁₃	H	4	78 (89 : 11)	
2	Ph	Me	24	51 (91 : 9)	

^a The reactions were performed with acetylene (1.1 mmol), Me₃In (1.5 mmol), allyl chloride (1.0 mmol) and Ni(acac)₂ (5 mol%).
^b Yields and the ratios of products were determined by GC.

**Scheme 1** Reaction mechanism for the formation of **1**.

At present the reaction mechanism of the bis-allylation remains unclear. π-Allylnickel intermediates have to be generated from not allyl chloride but (allyl)₃In. As a π-allylnickel reagent can be prepared from nickel(II) with allyl Grignard bromide,⁴ a transmetalation of (allyl)₃In with Ni(acac)₂ to a π-allylnickel compound seems to be feasible. It is notable that (i) Ni(acac)₂ showed, although not efficient, a catalytic activity (Table 1, entries 2 and 3) and (ii) the reaction can start with a nickel(0) catalyst (Table 1, entry 9). These results could be rationalized by assuming that an alternative path generating a π-allylnickel compound from nickel(0) and (allyl)₃In operates during the bis-allylation.⁷

In conclusion, we have demonstrated that the reaction of internal alkynes with triallylindium in the presence of nickel catalyst affords the *cis*-bis-allylated products in high yield. Further studies on details of this reaction and applications for other C–C unsaturated bonds are in progress.

We are grateful to the Ministry of Education, Sports, Culture, Science, and Technology, Japan Government, for Grant-in-Aid for Scientific Research, No. 14340195 for financial support.

Notes and references

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- Representative experimental procedure* (Table 1, entry 6): All reactions were performed under argon atmosphere. 1. *Preparation of In(allyl)₃*: To a solution of InCl₃ (0.22 g, 1.0 mmol) in THF (5.0 mL), allylmagnesium bromide (1.0 M, 3.0 mL, 3.0 mmol, Et₂O solution) was added at –78 °C. The reaction mixture was kept at the temperature for 1 h and another 1 h at room temperature before use. 2. *Reaction of alkyne with triallylindium*: Ni(acac)₂ was obtained from Ni(acac)₂·2H₂O (150 mg, 0.50 mmol) by heating with a heat gun *in vacuo*. To a solution of Ni(acac)₂ in THF (5.0 mL), the aforementioned solution of triallylindium (1.0 mmol), 1-phenylprop-1-yne (62 μL, 0.50 mmol), PhCH₂Ph (10 μL, standard material), and cycloocta-1,4-diene (125 μL, 1.0 mmol) were added at 0 °C.

The reaction mixture was refluxed for 16 h and the reaction was quenched with 1 M HCl (5.0 mL). The products were extracted with ether and washed with water and brine, and dried over Na₂SO₄. The yields were determined by GC analysis.

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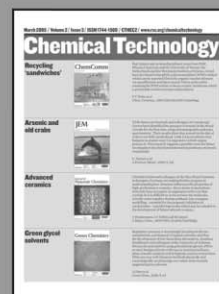
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7 A referee has suggested a possibility that triallylindium undergoes a disproportionation into In(allyl)₄⁻ and In(allyl)₂⁺ to explain the formation of π-allylnickel from triallylindium.

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